Mon. Not. R. Astron. Soc. **000**, 1–?? (2003) Printed 2 February 2008 (MN LaTeX style file v1.4)

On the Importance of Searching for Oscillations of the Jovian Inner Radiation Belt with a Quasi-Period of 40 Minutes

Yu-Qing Lou[!] [†] [*] and Chen Zheng[†]

[†] *Physics Department, Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, China*

[!] *National Astronomical Observatories, Chinese Academy of Sciences, A20, Datun Road, Beijing, 100012 China*

[*] *Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637 USA*

arXiv:astro-ph/0307276v1 14 Jul 2003

Accepted .... Received ...; in original form ...

ABSTRACT

Experiments aboard the Ulysses spacecraft discovered quasi-periodic bursts of relativistic electrons and of radio emissions with $\sim 40-$minute period (QP-40) from the south pole of Jupiter in February 1992. Such polar QP-40 burst activities were found to correlate well with arrivals of high-speed solar winds at Jupiter. We advance the physical scenario that the inner radiation belt (IRB) within $\sim 2-3$ Jupiter's radius R_J, where relativistic electrons are known to be trapped via synchrotron emissions, can execute global QP-40 magnetoinertial oscillations excited by arrivals of high-speed solar winds. Modulated by such QP-40 IRB oscillations, relativistic electrons trapped in the IRB may escape from the magnetic circumpolar regions during a certain phase of each 40-min period to form circumpolar QP-40 electron bursts. Highly beamed synchrotron emissions from such QP-40 burst electrons with small pitch angles relative to Jovian magnetic fields at $\sim 30-40R_J$ give rise to QP-40 radio bursts with typical frequencies $\lesssim 0.2$MHz. We predict that the synchrotron brightness of the IRB should vary on QP-40 timescales upon arrivals of high-speed solar winds with estimated magnitudes $\gtrsim 0.1$Jy, detectable by ground-based radio telescopes. The recent discovery of ~ 45-min pulsations of Jupiter's polar X-ray hot spot by the High-Resolution Camera (HRC) of the Chandra spacecraft provides a strong supporting circumstantial evidence that the IRB neighborhood did oscillate with QP-40 timescales. Using the real-time solar wind data from the spacecraft Advanced Composition Explorer (ACE), we show here that such QP-40 pulsations of Jupiter's polar X-ray hot spot did in fact coincide with the arrival of high-speed solar wind at Jupiter. We note also that a properly sampled data of simultaneous far-ultraviolet images of auroral ovals obtained by the Hubble Space Telescope imaging spectrograph (HST-STIS) would have contained QP-40 oscillatory signatures. By our theoretical analysis, we offer several predictions that can be tested by further observations.

Key words: inner radiation belt — Jupiter — magnetohydrodynamics — oscillations — solar wind — synchrotron emissions

1 INTRODUCTION

Quasi-periodic bursts of relativistic electrons (Simpson et al. 1992; McKibben et al. 1993; Desch 1994) and of accompanied radio emissions (MacDowall et al. 1993) were discovered by the Ulysses spacecraft a decade ago. The burst electron energy ranges from a few to $\gtrsim 10$ MeV and the frequency of radio bursts is usually $\lesssim 200$ kHz with occasional rises to ~ 700 kHz. These burst activities, characterized by a quasi-period of 40 minutes (QP-40), were inferred to occur in the south polar direction of Jupiter and were found to closely correlate with arrivals of high-speed solar winds at Jupiter (see figs. 11 and 12 of MacDowall et al. 1993; Bame et al. 1992). Polarizations of these radio bursts are predominantly right-handed. There were other evidence, though less certain, for Jovian QP-40 phenomena such as magnetic field fluctuations and proton fluxes from observations of various spacecraft (e.g., Balogh et al. 1992; Schardt et al. 1981).

Based on a theoretical magnetohydrodynamic (MHD) analysis, we proposed (Lou 2001) that the underlying physical mechanism may involve global QP-40 magnetoinertial oscillations of Jupiter's inner radiation belt (IRB) within

© 2003 RAS

$\sim 2 - 3R_J$. In the scenario of QP-40 IRB oscillations, several seemingly disparate key phenomena can be plausibly linked together. Variabilities from weeks to years of the Jovian system have been searched for in response to solar wind variations (e.g., Bolton et al. 1989; Miyoshi et al. 1999). The central question posed here is whether the synchrotron brightness of the IRB varies on QP-40 timescales and shorter ones resulting from solar wind speed variations at Jupiter.

The recent Chandra observations (Gladstone et al. 2002) detected QP-40 pulsations of north polar X-ray hot spots on Jupiter. From space, Cassini synchrotron radio observations at 2.2cm (Bolton et al. 2002) revealed relativistic electrons with energies $\gtrsim 50$ MeV inside the IRB. These observations provide a circumstantial evidence for QP-40 IRB oscillations. In this Letter, we derive physical consequences from empirical facts, provide relevant estimates, propose further observational tests, and establish that $\sim 45-$min pulsations of Jupiter's polar X-ray hot spot did coincide with an arrival of high-speed solar wind at Jupiter using the data from the spacecraft Advanced Composition Explorer (ACE). It would be significant to actively search for QP-40 IRB synchrotron brightness variations upon arrivals of high-speed solar winds at Jupiter using ground-based radio telescope facilities. Once established, this would enable us to study the dynamics of the IRB both observationally and theoretically from a new perspective.

2 THE PHYSICAL SCENARIO

By tracing QP-40 radio burst directions (MacDowall et al. 1993) in the plane of sky, comparing arrival times of various energetic particle species (Zhang et al. 1995), and analyzing electron anisotropies (Zhang et al. 1993), it is fairly certain that these charged particles bursted from Jupiter's south magnetic polar region. Jupiter has long been known to be an important source of relativistic electrons populating the heliosphere (Simpson et al. 1975; Nishida 1976). While specific aspects remain to be understood, the Jovian magnetospheric system interacting with the solar wind appears to be capable of producing relativistic electrons to supply the IRB and to compensate magnetic polar leaks.

What is then the origin or source of such polar QP-40 bursts of relativistic electrons and ions? By all accounts, it is plausible (Lou 2001) that QP-40 burst electrons and ions leak out from the narrow circumpolar zone separating the magnetic polar region with open magnetic fields from the adjacent Jovian IRB with closed magnetic fields. The IRB can trap relativistic electrons with energies up to $\sim$ 50MeV or higher, as inferred from IRB synchrotron emissions with wavelengths of $\sim 2.2 - 90$ cm (Bolton et al. 2002; de Pater 1984; Roberts et al. 1984; Sault et al. 1997). Moreover, by combined effects of Jupiter's fast rotation with a $\sim$ 10-hour period and a strong dipole magnetic field with a polar surface strength $|\vec{B}|$ of $\sim 10 - 14.4$G, the IRB is capable of magnetoinertial oscillations with periods of $\sim 40 - 50$ minutes and shorter ones (Lou 2001).

Such magnetoinertial oscillations of a rotating IRB involve both Lorentz and Coriolis forces. For low-frequency and large-scale oscillations, the mode frequency is hybrid of Alfvén and rotation frequencies; for high-frequency and small-scale oscillations, the mode frequencies are essentially those of globally trapped fast MHD waves. For the hybrid mode of the lowest frequency, the IRB plasma swings to and fro about the rotation axis.

With this scenario in mind, the gross overall correlations among QP-40 bursts of radio emissions (MacDowall et al. 1993), of relativistic electrons (Simpson et al. 1992; McKibben et al. 1993), of protons, and occasionally, of alphas (Zhang et al. 1995) seems to indicate that (i) QP-40 polar electron bursts are most likely responsible for QP-40 polar radio bursts, and (ii) a global resonant oscillatory mechanism may underlie the quasi-periodicity of ~ 40 min for polar bursts of relativistic electrons and ions (Schardt et al. 1981; Zhang et al. 1995).

To relate QP-40 IRB oscillations and QP-40 circumpolar bursts of electrons, we invoke large-scale asymmetries as well as small-scale irregulaties in magnetic field structures of the IRB (Lou 2001). During a certain phase of each IRB pulsation period, relativistic electrons may drift across thin vulnerable layers randomly spreading along circumpolar magnetic footpoints with a perpendicular gradient drift speed $\vec{\mathcal{R}}_\perp = -m_e\gamma v_\perp^2 c\vec{B}\times\nabla|\vec{B}|/(2eB^3)$ into a narrow circumpolar strip and thus give rise to an electron burst, where m_e is the electron mass, γ is the Lorentz factor, $v_\perp$ is the electron velocity perpendicular to $\vec{B}$, c is the speed of light, and e is the electron charge. Hence, QP-40 IRB oscillations lead to QP-40 bursts of relativistic electrons and ions from magnetic circumpolar zones. QP-40 radio bursts are then produced by highly beamed synchrotron radio emissions from such escaped relativistic electrons with very small pitch angles α (e.g., $\alpha \sim 6 - 4\times 10^{-3}$ at $\sim 30 - 40R_J$) relative to magnetic field lines such that radio burst frequencies are typically $\lesssim 200$ kHz detected by Ulysses (MacDowall 2001). It requires relativistic electrons of higher γ to produce occasional rising frequencies of up to $\sim$ 700 kHz at Ulysses. That onsets of QP-40 radio bursts (McKibben et al. 1993; Desch 1994) sometimes precede relevant electron bursts by $\sim 4-8$ min are likely caused by radio emissions from those relativistic electrons that travel along neighboring magnetic field lines but that are not intercepted by Ulysses (Lou 2001). Admittedly, we do not yet know details of circumpolar electron leak processes by lacking clues of magnetic field inhomogeneities and irregularities or defects.

3 THEORETICAL CONSIDERATIONS

In reference to observations, we now provide theoretical analyses and corresponding predictions.

3.1 Excitations of Global IRB Oscillations

Empirically, onsets of enhanced QP-40 burst activities correlate well with arrivals of high-speed solar winds at Jupiter (MacDowall et al. 1993). While the solar wind mass flux remains roughly constant for either fast or slow winds, variations in the wind speed U ($\sim 800 - 400$ km s^{-1}) cause the radial size of the sunward magnetosphere to change drastically ($\sim 50 - 100R_J$), where $R_J \cong 7.14\times 10^9$ cm. This offers a valuable clue for the excitation of QP-40 IRB oscillations and thus for the observed correlation of QP-40 polar burst activities with high-speed solar winds. Drastic changes

of solar wind speed at the Jovian magnetosphere or persistent Jovian magnetospheric compressions sustained during a high-speed solar wind phase with irregular intermittent relaxations caused by wind speed variations can both resonantly drive QP-40 magnetoinertial IRB pulsations and induce neighboring magnetic field oscillations (Balogh et al. 1992) through the conservation of the magnetospheric angular momentum (Nishida & Watanabe 1981). Such MHD pulsations of the IRB should then lead to QP-40 brightness variations.

3.2 Estimates for IRB Brightness Variations

The solar wind mass flux is estimated by $4\pi\rho U D_J^2$, where ρ is the wind mass density and D_J is Jupiter's distance to the Sun. Changing from slow to fast winds at Jupiter, the wind ram pressure ρU^2 increases by a factor of ~ 2. After a transient time of adjustment and for a negligible IRB thermal pressure, this increase of wind ram pressure is grossly balanced by an increase of magnetic pressure $B^2/(8\pi)$ of the IRB temporarily. Thus, the relative field strength variation $\delta B/B$ in the IRB may be as large as $\sim 40\%$ stirred by drastic solar wind speed variations; and by the magnetic flux conservation, the radial extent of the IRB may vary by $\sim 20\%$ accordingly.

In the IRB, for a power-law distribution of electron number density $N(\gamma) \propto \gamma^{-S} d\gamma$ in the energy interval $(\gamma, \gamma + d\gamma)$, the spectral intensity I_ν of radiation is $I_\nu \propto B^{(S+1)/2}\nu^{-(S-1)/2}$ (Ginzburg & Syrovatskii 1965; Rybicki & Lightman 1979). At a given frequency ν, one has $\delta I_\nu/I_\nu \cong (S+1)\delta B/(2B)$. For the Jovian IRB, the spectral index $S > 1$ and I_ν takes on values of $\sim 0.44 \pm 0.15$, ~ 3, $\sim 4.02 \pm 0.08$, and $\sim 5.15 \pm 0.7$Jy at $\nu = 13.8$, 5, 2.3, and 0.333 GHz, respectively (Bolton et al. 2002). Thus, in two separate frequency ranges $0.333 - 5$GHz and $5 - 13.8$GHz, $(S-1)/2 \sim 0.19$ and ~ 1.9, respectively. Conservatively, δI_ν is estimated to be $\gtrsim 0.1$Jy. As a crucial test, such QP-40 IRB brightness variations in wavelengths $\sim 6-90$ cm should be searched for using ground-based radio telescopes.

3.3 Polarization Properties of Radio Bursts

There are several physical reasons and observational tests to support and to further check our scenario. The radiation electric field $\vec{E}_{rad}$ from an accelerating electric charge q is given by (e.g., Rybicki & Lightman 1979)

$$\vec{E}_{rad}(\vec{r}, t) = \frac{q}{c}\left[\frac{\vec{n}}{\kappa^3 R} \times \{(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}\}\right], \qquad (1)$$

where brackets denote variables at retarded times, $\vec{\beta} \equiv \vec{u}/c$ is the particle velocity normalized by c, $\dot{\vec{\beta}}$ is the time derivative of $\vec{\beta}$, $\vec{n}$ is the unit vector along the line of sight distance R at retarded times, and $\kappa \equiv 1 - \vec{n}\cdot\vec{\beta}$. The radiation magnetic field is $\vec{B}_{rad}(\vec{r}, t) \equiv [\vec{n} \times \vec{E}_{rad}(\vec{r}, t)]$. The south polar magnetic field $\vec{B}$ points towards the Jupiter. For a relativistic electron streaming outward from the south pole with a small pitch angle α (nearly anti-parallel to $\vec{B}$), the instantaneous $\vec{E}_{rad}$ is nearly along $\dot{\vec{\beta}}$. Given an electron's right-hand gyration with respect to $\vec{B}$, the radio polarization at Ulysses should be right-handed; this qualitative conclusion has also been confirmed by more detailed numerical computations. This right-handed radio polarization should prevail for a bunch of electrons so long as their spatial distribution is not completely random. This theoretical result is consistent with the Ulysses Radio and Plasma Wave Experiment (URAP) observations (MacDowall 1993).

In year 2004, Ulysses will have a second rendezvous with Jupiter in the northern heliosphere with a closest approach of $\sim 1000R_J$. For global IRB oscillations and qualitatively similar polar $\vec{B}$ configurations as well as level of irregularities, QP-40 bursts of relativistic electrons and of accompanied radio emissions from the north pole are anticipated, especially during arrivals of high-speed solar winds at Jupiter. While Ulysses particle instruments cannot intercept QP-40 bursts of relativistic electrons (one still expects to observe a gradual increase of relativistic electron flux towards Jupiter), URAP will have a good opportunity to observe north polar QP-40 radio bursts outside the Jovian magnetosphere. As $\vec{B}$ points outward from the Jovian north pole, we predict that polarizations of north circumpolar QP-40 radio bursts should be predominantly left-handed.

3.4 Frequencies of QP-40 Radio Bursts

Let us now estimate typical frequency components of a radio burst. As relativistic electrons leak out quasi-periodically during a certain phase in each period of IRB QP-40 oscillations, radio burst emissions are produced by the synchrotron process from relativistic electrons in nearly anti-parallel motions outward along south polar magnetic field lines. Such IRB relativistic electrons initially drift across the narrow circumpolar zone about the magnetic axis and they gyrate transverse to the local surface $\vec{B}$, radiating intensely in a perpendicular plane due to the relativistic beaming effect (i.e., strongest emissions within an angle $\lesssim 1/\gamma$ about $\vec{v}$ direction). The total power emitted by an electron is $P(\gamma) = 2(\gamma^2 - 1)e^4 B^2 \sin^2\alpha/(3m_e^2 c^3)$.

As electrons stream outward from circumpolar magnetic footpoints with gyroradii $r_c \sim \gamma m_e c^2/(eB) = 1.7 \times 10^3 \gamma B^{-1}$ cm $\ll R_J$, the magnetic mirror force rapidly converts transverse gyrations to parallel motions by conserving both particle energy $\mathcal{E} \equiv \gamma m_e c^2$ and magnetic moment $\mathcal{E}_\perp/|\vec{B}|$ where $\mathcal{E}_\perp$ is the kinetic energy of transverse gyration. The synchrotron emission cone ahead of a relativistic electron gyrating around $\vec{B}$ shrink in conal angle towards the forward direction of $\vec{v}$ with decreasing characteristic frequencies (Ginzburg & Syrovatskii 1965).

For a dipole magnetic field $|\vec{B}| \propto r^{-3}$ and a polar surface $|\vec{B}|$ strength of ~ 10G, the pitch angle α of electrons, independent of γ, becomes $\sim 6 \times 10^{-3}$ at $\sim 30R_J$ or $\sim 4 \times 10^{-3}$ at $\sim 40R_J$. The characteristic synchrotron emission frequency ν_c from a gyrating electron is given by $\nu_c = 0.29 \times 3\gamma^2 eB \sin\alpha/(4\pi m_e c)$ (Rybicki & Lightman 1979). For parameters of interest, we have $\nu_c \sim 3\gamma^2$ and $\sim 0.87\gamma^2$ at $\sim 30R_J$ and $\sim 40R_J$, respectively. For typical spectral profiles of QP-40 radio bursts, the dominant peak falls between $\sim 10 - 80$kHz (MacDowall et al. 1993). ⋆ For

⋆ A reduced intensity at about $40-50$ kHz may not be a common feature of the QP-40 bursts. The transition from the URAP RAR Low to High band receivers occurs at ~ 50 kHz.

a power-law number distribution of IRB electrons in γ, this would imply relativistic electrons with a γ range of as high as $\sim 160 - 300$. The recent Cassini synchrotron observation in space at 2.2cm (13.8GHz) revealed electron energies of $\sim$ 50MeV inside the IRB, with further hints of a high-energy tail with $\gamma \gtrsim 200$ at $r \gtrsim 2R_J$ (Bolton et al. 2002). If $\sin\alpha$ is taken to be ~ 1 as commonly assumed, then ν_c would be much higher than several hundred kilohertz.

3.5 QP-40 Pulsations of Polar X-Ray Hot Spots

With both magnetic poles being qualiatively equal, we focus on pulsations of northern auroral X-ray hot spot of Jupiter with a $\sim$ 45-minute period discovered lately (Gladstone et al. 2002) using the high-resolution camera (HRC) of the Chandra X-ray Observatory on 18 December 2000. While physical processes leading to such polar X-ray hot spots inside the main far-ultraviolet (UV) polar auroral oval are currently unexplained, their QP-40 pulsations nontheless offer extremely valuable diagnostics for probing the inner magnetospheric environment.

In the scenario of QP-40 IRB oscillations (Lou 2001), the northern auroral X-ray hot spots should pulsate with a quasi-period of $\sim$ 40 min as QP-40 magnetoinertial oscillations of the IRB will affect, through fast MHD wave transmissions, the immediate environs that include circumpolar zones of open magnetic fields, and leave QP-40 oscillatory signatures there (Balogh et al. 1992). Almost certainly, $\sim$ 45-min pulsations of southern auroral X-ray hot regions were not seen this time (Gladstone et al. 2002) primarily owing to an unfavorable viewing geometry from the Chandra HRC. We anticipate that, similar to QP-40 polar burst activities and IRB oscillations (MacDowall et al. 1993), pulsation magnitudes of such X-ray hot spots poleward of the far-UV auroral oval should be also enhanced upon arrivals of high-speed solar winds at Jupiter. One primary goal of the Chandra and HST campaigns supporting the Cassini fly-by is to search for connections between Jovian auroral transients and the interaction of the solar wind with Jupiter's magnetosphere; in fact, this is already in hand but not yet fully appreciated.

It is promising to pursue a direct detection of Jupiter's QP-40 IRB brightness variations in the wavelength range of $\lambda \sim 6 - 90$ cm with magnitudes $\gtrsim 0.1$Jy by the ground-based radio telescope facilities such as those at Effelsberg, Very Large Array, Westerbork Synthesis Radio Telescope, Owen's Valley Radio Observatory, and Australia Telescope Compact Array. The optimal condition for a detection can be derived in advance by combining the information of locations of the Earth and the Jupiter relative to the Sun and the knowledge of low-latitude solar X-ray coronal holes where fast solar winds emanate. As the Sun rotates with an equatorial period of $\sim 25-26$ days, fast solar wind streams recur in the interplanetary space (Lou 1994, 1996). Meanwhile, it is crucial to establish the correlation of QP-40 pulsations of polar X-ray hot spots with arrivals of high-speed solar winds using the Chandra HRC. As Jovian auroral ovals mark the boundary zones separating the closed $\vec{B}$ of IRB and the open polar $\vec{B}$, it is inevitable that far-UV auroral ovals may pulsate with a QP-40 period upon arrivals of high-speed solar winds; this prediction can be tested by Hubble Space Telescope imaging spectrograph (HST-STIS) observations. †

3.6 Coincidence with a High-Speed Solar Wind

For the Chandra HRC 10-hour observation for X-ray QP-40 pulsations of Jupiter's polar hot spot on 18 December 2000 from 10-20 UT (Gladstone et al. 2002), we show that this observation run happened to coincide with an arrival of high-speed wind at Jupiter. We obtained pertinent information from the website ssd.jpl.nasa.gov/ under Mean Orbital Elements for both the Earth and Jupiter, and from the websites www.sec.noaa.gov/ace/ACErtsw_home.html and www2.crl.go.jp/uk/uk223/service/arc/ for the archival data of real-time solar wind properties measured by the ACE spacecraft. On 12:00 noon of 1 January 2000, the Earth longitude $L_E = 100.46435$ deg and the Jupiter longitude $L_J = 34.40438$ deg, respectively. The mean angular rate of the Earth is $129597740.63''$/100yr= $3548.1928''$/day=0.9856091 deg/day and the mean angular rate of the Jupiter is $10925078.35''$/100yr=$299.11234''$/day =0.08308676 deg/day. On 12:00 noon of 18 December 2000, $L_E = 87.398753$ deg and $L_J = 63.65092$ deg. A high-speed wind of ~ 700 km s^{-1} present at Jupiter on 12:00 noon of 18 December 2000 should imply the leading edge of a low-latitude coronal hole at longitude $L_H = 62.65$ deg on 2:24 AM of 6 December 2000. As the equatorial angular rotation rate of the Sun is $\sim$ 27 days, a high-speed wind of ~ 700 km s^{-1} is estimated to reach the Earth after 3:00 PM of 9 December 2000. According to the ACE data for the real-time solar wind speed U in unit of km s^{-1}, we have $390 \lesssim U \lesssim 450$, $550 \lesssim U \lesssim 650$, $650 \lesssim U \lesssim 700$, $700 \gtrsim U \gtrsim 600$, $600 \gtrsim U \gtrsim 540$, $550 \gtrsim U \gtrsim 430$, $440 \gtrsim U \gtrsim 400$, $U \sim 390$, $380 \gtrsim U \gtrsim 320$, and $U \sim 330$ on $7-16$ December 2000, respectively. So a high-speed solar wind of ~ 700 km s^{-1} did indeed arrive the Earth on 9 and 10 December 2000 by the ACE data.

As the polar X-ray hot spot is near the IRB, this observed result is consistent with the scenario that QP-40 IRB oscillations are excited more prominently at the arrival of high-speed solar wind. We need more Chandra HRC observations and correlation studies with the ACE solar wind speed data to firmly establish this important revelation. As the Jovian auroral ovals separate closed magnetic fields of the IRB from open magnetic fields of the pole, it is natural to expect that the far UV auroral ovals around the Jovian magnetic poles should also oscillate with a QP-40 period by the HST-STIS observations during that period of time.

4 SUMMARY AND CONCLUSIONS

Based on empirical clues, intuitive considerations, and theoretical analysis, it is physically plausible and appealing that polar QP-40 bursts of relativistic electrons and radio emissions involve global QP-40 IRB oscillations of Jupiter. With

† Grodent, et al. (2001) indicated in their AGU Spring Meeting abstract #P52A-09 that the sampling of the HST-STIS at the time did not permit them to highlight a forty-minute oscillation in the corresponding ultraviolet light curve.

this scenario in mind, we summarize below key results and testable predictions.

(1) QP-40 burst electrons, protons, and alpha particles with relativistic energies most likely originated from the Jovian IRB (Lou 2001) where relativistic electrons with γ as high as $\sim 100-200$ are known to exist (Bolton et al. 2002). They escape from the Jovian circumpolar region and are modulated by global QP-40 IRB oscillations. Some of escaping relativistic electrons may attain large γ as indicated.

(2) As estimated here, the predicted QP-40 brightness variations of the IRB should be observable by existing ground-based radio telescopes. It is extremely important to verify the expected correlation of such QP-40 brightness variations with arrivals of high-speed solar winds. Under favorable situations, higher harmonics of QP oscillations with shorter periods (Lou 2001) might also be detectable.

(3) The QP-40 IRB oscillations are most likely excited and sustained by the combined effects of solar wind speed variations, of short-term intermittent wind speed variations during either fast or slow wind phase, and of angular momentum conservation of Jovian magnetospheric plasma.

(4) Assuming a similar level of inhomogeneities for both north and south polar magnetic fields, we predict QP-40 bursts of relativistic electrons of the IRB from Jupiter's north polar region. Moreover, such QP-40 north polar activities are expected to correlate well with arrivals of high-speed solar winds at Jupiter. In coordination with spacecraft observations of solar wind properties, another spacecraft needs to be launched to enter Jovian magnetosphere and to probe the north polar region in order to test this prediction.

(5) At $30-40R_J$ away from the Jupiter, synchrotron emissions with small pitch angles α are stronger than curvature emissions in QP-40 radio bursts associated with relativistic electrons streaming along south polar magnetic field lines of Jupiter. The observed predominance of right-handed polarization of radio burst emissions is consistent with the gyration sense of outstreaming electrons in the south polar magnetic field pointing towards Jupiter. North polar QP-40 radio bursts associated with north polar QP-40 bursts of relativistic electrons are expected and should be detectable by Ulysses, now approaching the Jupiter in the northern heliosphere. Because Jupiter's north polar magnetic field points outward, we thus predict the polarization of north polar QP-40 radio bursts to be predominantly left-handed. These predictions can be tested by Ulysses observations in the near future (year 2003-2004).

(6) Based on one case of coincidence of QP-40 pulsations of north polar X-ray hot spots with an arrival of high-speed solar wind at Jupiter and our global QP-40 IRB oscillation scenario, we would like to emphasize the importance of empirically establishing this correlation through more coordinated spacecraft observations.

(7) Latitudewise, the Jovian auroral ovals lie between the IRB and the polar X-ray hot spots. Through magnetospheric wave transmissions of IRB oscillations to neighboring polar magnetic fields, we naturally expect QP-40 pulsations of Jovian aurora ovals in correlation with arrivals of high-speed solar winds at Jupiter. For example, this prediction can be tested by well-prepared HST-STIS observations of FUV auroral ovals with appropriate sampling rate.

By this Letter, we hope to stimulate more observational and theoretical studies on QP-40 polar activities of Jupiter and to identify the physical cause of QP-40 phenomena.

ACKNOWLEDGMENTS

This research has been supported in part by the ASCI Center for Astrophysical Thermonuclear Flashes at the University of Chicago under Department of Energy contract B341495, by the Special Funds for Major State Basic Science Research Projects of China, by the Collaborative Research Fund from the NSF of China (NSFC) for Young Outstanding Overseas Chinese Scholars (NSFC 10028306) at the National Astronomical Observatory, Chinese Academy of Sciences, and by the Yangtze Endowment from the Ministry of Education through the Tsinghua University. Affliated institutions share this contribution.

REFERENCES

Balogh A., et al., 1992, Science, 257, 1515
Bame S. J., et al., 1992, Science, 257, 1539
Bolton S. J., et al., 1989, J. Geophys. Res., 94, 121
Bolton S. J., et al., 2002, Nature, 415, 987
Coroniti F. V., 1975, Space Sci. Rev., 17, 837
de Pater I., 1990, ARA&A, 28, 347
Desch M. D., 1994, ApJS, 90, 541
Ginzburg V. L., Syrovatskii S. I., 1965, ARA&A, 3, 297
Gladstone G. R., et al., 2002, Nature, 415, 1000
Gurnett D. A., et al., 2002, Nature, 415, 985
Lou Y. Q., 1994, J. Geophys. Res., 99, 14747
Lou Y. Q., 1996, Geophys. Res. Lett., 23, 609
Lou Y. Q., 2000, ApJ, 540, 1102
Lou Y. Q., 2001, ApJ, 548, 460
MacDowall R. J., et al., 1993, Planet. Space Sci., 41, 1059
McKibben R. B., Simpson J. A., Zhang M., 1993, Planet. Space Sci., 41, 1041
Miyoshi Y., et al., 1999, Geophys. Res. Lett, 26, 9
Nishida A., 1976, J. Geophys. Res., 81, 1771
Nishida A., Watanabe Y., 1981, J. Geophys. Res., 86, 9945
Northrop T. G., 1963, The Adiabatic Motion of Charged Particles. Interscience Publishers, New York
Roberts J. A., Berge G. L., Bignell R. C., 1984, ApJ, 282, 345
Rogers J. H., 1995, The Giant Planet Jupiter. Cambridge University Press, Cambridge, England
Rybicki G. B., Lightman A. P., 1979, Radiative Processes in Astrophysics. John Wiley & Sons, New York
Sault R. J., Oosterloo T., Dulk G. A., Leblanc Y., 1997, A&A, 324, 1190
Schardt A. W., McDonald F. B., Trainor J. H., 1981, J. Geophys. Res., 86, 8413
Schultz M., Lanzerotti L. J., 1974, Particle Diffusion in the Radiationa Belts. Springer Verlag, New York
Simpson J. A., et al., 1975, Science, 188, 455
Simpson J. A., et al., 1992, Science, 257, 1543
Stone R. G., et al., 1992, Science, 257, 1524
Walt M., 1994, Introduction to Geomagnetically Trapped Radiation. Cambridge University Press, Cambridge
Zhang M., et al., 1995, J. Geophys. Res., 100, 19497
Zhang M., Simpson J. A., McKibben R. B., 1993, Planet. Space Sci., 41, 1029